ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 10 (2011) 3799–3804
Engineering Procedia

ICM11

Effect of laser remelting on the mechanical behav[illegible]ur of Inconel 625 cold-sprayed coatings

P. Poza[a*], C. J. Múnez[a], M. A. Garrido[a], S. Vezzù[b], S. Re[illegible][b], A. Trentin[b]

[a]Departamento de Ciencia e Ingeniería de los Mate[illegible].
Universidad Rey Juan Carlos.
Escuela Superior de Ciencias Experimentales y [illegible]nolog[illegible]
C/ Tulipán s.n. 28933 Móstoles (Madrid) SPAIN
[b]Associazione Civen[illegible]
via delle industrie, 5,30157 Marg[illegible]a (VE), ITALY

Abstract

Ni based coatings are being used to protect metalli[illegible]ering components in extreme conditions. Cold gas dynamic spray, or simply cold spray, i[illegible]ng inc[illegible]d attention during the last years because of the lower spraying temperature required to dep[illegible] metal[illegible] coatings[illegible]rther improvements in the coatings' performance could be attained by laser glazing to enh[illegible] coatin[illegible] adhesion a[illegible] oxidation resistance. For these reasons, the aim of this work is to analyse the viabilit[illegible] of [illegible] to p[illegible]s Inconel 625 coatings and to evaluate the effect of laser remelting on their mechanic[illegible]operties.

Selection and peer-[illegible]ew[illegible]der respons[illegible]lity of ICM11
"Keywords: cold spra[illegible] laser treatme[illegible]pth sensing indentation (nanoindentation); SEM"

1. Introd[illegible]n

[illegible]d coa[illegible] ar[illegible]eing extensively used to improve the oxidation and corrosion resistance, as well [illegible]e w[illegible] perfor[illegible]e, of less expensive materials like medium alloy steels [1,2]. Inconel 625 coatings [illegible]und n[illegible] industrial applications in chemical and petrochemical plants [1], as well as in the power g[illegible]on sec[illegible] [2] to protect turbine components operating in extreme conditions, which include high

* Corresponding author. Tel.: +34 914 887 179; fax: +34 914 888 150.
E-mail address: pedro.poza@urjc.es.

1877-7058 © 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of ICM11 doi:10.1016/j.proeng.2011.06.002

temperature and an aggressive environment. The advantages to use coatings deposited onto less expensive materials is the significant costs reductions compared to use bulk alloys.

Thermal spraying methods are the most extended processing techniques for Ni based coatings used in industrial applications. In particular, high velocity oxy-fuel (HVOF) is the most extended method to processes Inconel 625 coatings [1,2]. This method, as well as other high temperature spraying techniques, like plasma spraying (PS), could deteriorate the substrate properties by the high temperatures involved and could promote partial oxidation of the metallic powders, if a protective environment is not used. Cold gas dynamic spray, or simply cold spray (CS), is receiving increased attention during the last years because of the lower spraying temperature required to deposit metallic coatings. CS is a solid-state powder deposition process, which does not require a protective environment to produce coatings with reduced oxides content, low residual stresses and high efficiency [3]. For these reasons CS has been evaluated to produce several Ni rich coatings with improved performance at high temperature [2,4]. However, to the author knowledge, there are no publications about CS Inconel 625 coatings.

Further improvements in the coatings' performance could be attained by post-deposition treatments to enhance coating adhesion and to reduce interconnected porosity. In this sense laser glazing could be used to perform a local thermal treatment on the top of the coating reducing surface roughness and sealing open porosity [5,6]. Laser remelting homogenize the microstructure removing splat-structure, typical in high temperature thermal sprayed coatings, and reducing interconnected porosity, which promote an increased oxidation and corrosion resistance [6]. However, laser glazing could modify the coatings microstructure, in a metallurgical sense, as the Ni based alloy is melted and rapidly solidified. These microstructural changes will affect the coating's mechanical performance.

For these reasons, the aim of this work is to analyze the viability of CS to process Inconel 625 coatings. In addition, the effect of laser remelting on the mechanical properties of these coatings will be evaluated by nanoindentation.

2. Experimental techniques

2.1. Materials

Inconel 625 coatings have been deposited onto AISI304 plate substrates. The substrates have been prepared by sandblasting using corundum 16 mesh and then washed in ultrasonic bath with acetone to remove greases and residual corundum particles. A commercial gas atomized Inco625 powder, specifically designed for cold spray deposition, has been supplied by Sandvik Osprey Ltd with size distribution -38+15 μm. This powder had good sphericity, necessary to ensure good particle flowability during spraying.

2.2. Cold spraying

The coatings were deposited using a commercial CGT Kinetics 3000 series Cold spray system with a tungsten carbide MOC De Laval nozzle and nitrogen as propellant gas. The gun was equipped with a short pre-chamber tube in order to increase the particle temperature and as a consequence to allow a thermal softening effect improving the ductility of the sprayed powders. Gas temperature was kept at 500 °C, while the gas flow was fixed at 80 m^3/h and the related pressure at 32-33 bar. The standoff distance to the substrate was 20 mm.

2.3. Laser remelting

Laser remelting was carried out on the Inconel 625 cold sprayed coatings by high power diode laser (HPDL) ROFIN-SINAR 13DS, with maximum power of 1.3 kW and a wavelength of 940 nm. The laser head was placed on an anthropomorphic robot and was used to generate resolidified structures with different heat inputs. The laser power was kept constant at 700 W and the scan speed was varied in the range of 25-50 mm/s. The different single tracks were performed in a shielding atmosphere of Ar.

2.4. Nanoindentation test

To determine the mechanical properties of cold sprayed coatings and the welded beads obtained by laser remelting, nanoindentation technique has been used. The experimental device utilized is a Nanoindenter XP (MTS System Co.). This instrument applies load via a calibrated electromagnetic coil with a resolution of 50 nN. The displacement of the indenter is measured using a capacitive plate transducer with a resolution of 0.01 nm.

Prior to make the indentations on the cold sprayed coating and remelted lines, a calibration procedure was carried out on a commercial bulk Inconel 600 alloy according to continuous stiffness measurement methodology (CSM) using a diamond Berkovich tip [7,8]. Nominal elastic modulus was set to 214 GPa.

Indentation lines, longitudinal and transversal to the beads direction, were carried out using a diamond Berkovich tip. Five loading and unloading cycles were applied in each indentation up to maximum indentation load of 100 mN. The indentations were separated from each other by a distance of 80 μm, ensuring that there was no interaction between strain fields of two consecutive indentations. From each unloading curve, modulus of elasticity, E, and hardness, H, were derived following the Oliver-Pharr method [8]. Thus, five values of both mechanical properties were obtained from each indentation as a function of the penetration depth. In order to detect the indentations affected by the presence of porosity and defects, the elastic modulus values, obtained from each indentation test, were plotted versus penetration depth. Those indentations whose elastic modulus varied with the indentation depth were not considered for the data analysis. The hardness decreases with the penetration depth. This phenomenon is commonly known as the indentation size effect [9]. The hardness decreases gradually with the penetration depth until it reaches an asymptotic value. In this work, the hardness value obtained from the unloading branch of the last cycle was considered as the asymptotic value of the hardness. This value was used for the results analysis.

2.5. Microstructural characterization

Polished samples of both as-deposited cold sprayed coatings and the laser remelted tracks were analysed in an Hitachi S-3400 scanning electron microscope (SEM), equipped with energy dispersive X-ray microanalysis (EDX). The polished samples were conventionally etched.

3. Results

3.1. Microstructure of Cold Sprayed coatings

The as-sprayed coating showed a lamellar structure of thermally sprayed process (figure 3a), with a characteristic porosity and splats boundaries. Moreover, high deformation and cold work can be seen in figure 3b and a dendritic microstructure was observed inside the deformed particles.

3.2. Microstructure of laser remelted coatings

After laser remelting at different scanning speeds, the coating obtained is dense with a significant reduction of porosity, free of cracks and fine columnar dendritic microstructures (Fig 3b). The low secondary arms spacing, around 1 μm, showed the very high cooling rate achieved during solidification. EDX revealed that bright interdendritic areas were enriched in Nb and Mo. These solutes elements accumulated in front of the liquid-solid interface and segregated to the interdendritic areas during solidification.

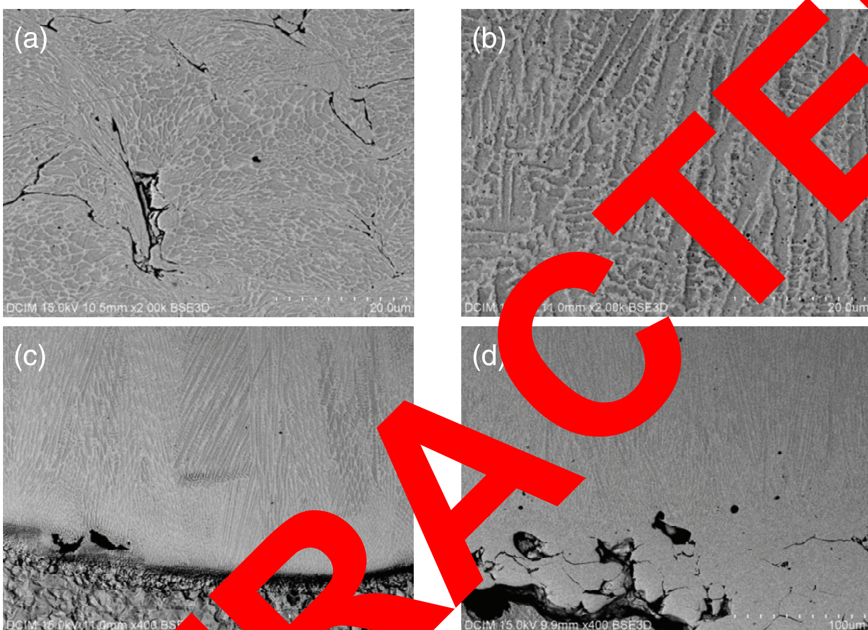

Fig. 3. SEM images of the as sprayed and laser remelted Inconel 625 coatings. a) As sprayed coating showing a cold worked dendritic microstructure; b) columnar dendritic microstructure close to surface in the laser remelted coating, scanning speed 25 mm/s; c) Substrate/coating area with substrate remelting at 25 mm/s; d) Substrate/coating area without substrate remelting at 45 mm/s.

Substrate remelting was observed in substrate/coating zone (Fig. 3c) at lower laser scan speed range (25-35 mm/s), however at higher scan speed range (40-50 mm/s), the laser treatment did not affect to the stainless steel substrate because heat inputs were lower (Fig. 3d). EDX analysis close to surface regions revealed that the substrate melting modifies the alloy elements and its proportions in the laser remelted bead, with a significant increase of Fe content.

3.3. Nanoindentation

The elastic modulus and hardness values remained constant with the distance along the bead path in the indentation lines performed longitudinally. On the other hand, the elastic modulus and hardness values sketched a profile of mechanical properties, sensitive to the presence of the coating and bead regions, in the transversal indentations lines. Finally, the mechanical properties remained constant in the cold spray coating and inside of each bead. The average value of both mechanical properties was calculated for each zone and these values are summarized in table 2.

4. Discussion

The Young's moduli measured in the CS Inconel 625 were similar to those expected in the bulk alloys (E≈214 GPa). However, the hardness values obtained in the cold sprayed materials were [illegible], around twice, than those corresponding to the bulk alloy (H≈3.3 GPa). This result was [illegible] to the high deformation induced during CS which will work-harden the metallic alloy. An increased value of hardness could be beneficial for the wear performance.

The metallic alloy was melted and rapidly solidified during laser treatment. As a consequence, the coating's microstructure was modified leading to a less porous material and to a columnar dendritic microstructure. The reduction in porosity increased the elastic modulus of the Inconel 625 coatings and this increment reached approximately a 10 % in the most energetic conditions, corresponding to the 25, 30 and 35 mm/s scan speeds. The elastic modulus increased around a [illegible] for the 40, 45 and 50 mm/s scan speeds. As it could be expected, the reduction in porosity was higher as the treatment was more energetic.

In addition, the columnar dendritic microstructure reduced the hardness of the coating, although the values measured are still higher than those corresponding to the bulk alloy. Hardness was reduced approximately a 30% when the scan speeds were 40, 45 and 50 mm/s, while this reduction was only around a 20% for the more energetic conditions corresponding to 25, 30 and 35 mm/s scan speeds. The higher hardness measured in these last conditions could be explained because the laser treatment affected the steel substrate. Consequently, the Fe content in the coating increased leading to an increment in hardness compared with the other laser treatment conditions.

Table 2. Average values of elastic modulus and hardness obtained from depth sensing indentation tests on the different zones. The values between parentheses represent the corresponding standard deviations. Variation, in percentage, of the elastic modulus and hardness values obtained on the beads relating to the ones obtained on the coating, are also included.

Zone	Elastic modulus (GPa)	Hardness (GPa)	Elastic modulus variation (%)	Hardness variation (%)
LR-1	233 (7)	[illegible]	+9	-22
Coating	213 (11)	7.58 (0.27)	—	—
LR-2	[illegible] (5)	6.28 (0.23)	+12	-18
Coating	209 (16)	7.20 (0.31)	—	—
LR-3	230 [illegible]	6.29 (0.35)	+12	-16
Coating	[illegible] (9)	7.44 (0.18)	—	—
[illegible]	222 [illegible]	5.69 (0.28)	+7	-31
Coating	213 (10)	7.45 (0.37)	—	—
[illegible]	[illegible] (7)	5.68 (0.35)	+6	-31
Coating	210 (10)	7.50 (0.35)	—	—
LR-6	222 (9)	5.57 (0.32)	+7	-34
Coating	205 (11)	7.39 (0.22)	—	—

5. Conclusions

Laser glazing was applied to Inconel 625 coatings deposited by CS onto AISI 304 steel substrates. The mechanical properties were analysed by depth sensing indentation, leading to the following conclusions:

- CS is a thermal spraying method suitable to process Inconel 625 coatings onto steel substrates. The hardness of the cold sprayed Inconel 625 coatings is higher than that corresponding to bulk alloys.
- Laser glazing reduces interconnected porosity in the coatings, which will probably affect beneficially the corrosion and oxidation resistance of these protective systems. This reduction in porosity [illegible]ed the elastic modulus of the coatings and is more evident as the energetic conditions [illegible] the la[illegible] treatment are increased.
- The laser remelted samples exhibited a columnar dendritic microstructure which re[illegible]uces [illegible]hardness of the coating, although the values measured are still higher that those corre[illegible]nding to [illegible] bu[illegible] alloys.
- The hardness reduction is less important in the samples treated in the [illegible] en[illegible]tic conditions; because of the laser treatment affected the steel substrate. Consequently [illegible] was [illegible]sed to [illegible]oating. Although these conditions improved the hardness of the coating, the[illegible]e not the [illegible] s[illegible]ble as this benefit is a consequence of the substrate affectation.

Acknowledgements

The authors would like to thank the Spanish government CICYT thro[illegible] grant MAT2[illegible]-18916, *Universidad Rey Juan Carlos* through the project “Comportamiento de recubrimientos con aplicaciones a [illegible]mperat[illegible] and Comunidad de Madrid through the program ESTRUMAT-CM for financial support.

References

[1] Bolelli G., Lusvarghi L., Giov[illegible]i R., A[illegible]mparison [illegible]veen the corrosion resistances of some HVOF-sprayed metal alloy coatings, Surf. Coat. Technol. 200[illegible] 479[illegible]

[2] Sampath S., Jiang X.Y[illegible]atejic[illegible]chlik L., Kulkarni A., Vaidya A., Role of thermal spray processing method on the microstructure, residual st[illegible]nd propertie[illegible]coatings: an integrated study for Ni–5 wt.%Al bond coats, Mater. Sci. Eng. 2004; A364: 216–31.

[3] Papyrin A., Kosarev V., [illegible]y S., Alkhimov A. and Fomin V. Cold spray technology. Elsevier; 2007.

[4] Bala N.[illegible]gh H., Prakash [illegible]gh-temperature oxidation studies of cold-sprayed Ni–20Cr and Ni–50Cr coatings on SAE 213-T22 b[illegible] steel, A[illegible]pl. Surf. Sci. 2[illegible]09; 255: 6862–69.

[5] S[illegible] J., T[illegible]nen J., Vuoristo P. Laser-assisted spraying and laser treatment of thermally sprayed coatings. Surf. Coat. Technol. 2[illegible]: 1981–8[illegible]

[6] [illegible]med [illegible]kare[illegible]., McCartney D.G., Voisey K.T. The effects of microstructural features on the performance gap in c[illegible]sion re[illegible]ance bet[illegible]lk and HVOF sprayed Inconel 625. Surf. Coat. Technol. 2010; 204: 2294–301.

[7] [illegible] X., Bhushan B., A review of nanoindentation continuous stiffness measurement technique and its applications. Mater. C[illegible]002; 48[illegible]6.

[8] Oliver, W.C., Pharr, G.M., An improved technique for determining hardness and elastic modulus using load and displace[illegible]ensing indentation experiments, J. Mater. Res. 1992; 7: 1564-83.

[9] Elmustafa A. A., Stone D. S., Indentation size effect in polycrystalline F.C.C. metals, Acta Mater. 2002. 50: 3641-50.